MERCURY 2000: STEREOSCOPIC OBSERVATIONS OF GAMMA RAY FLARES

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Abstract

Stereoscopic observations of gamma ray radiation from solar flares would provide further scientific impetus to recent proposals for a planetary observer mission to Mercury in the late 1990's. The solar monitoring phase of this mission could continue through the period of maximum flare activity in the years 2002-2006 with a dawn-dusk polar orbit which would allow continuous solar visibility and minimize solar tracking requirements. Simultaneous measurements of flare radiation from gamma ray instruments with comparable solar flux sensitivity in orbits around Mercury and Earth would provide stereoscopic information on directivity and altitude location in the solar atmosphere of the flare radiation sources and might significantly advance understanding of energy release and particle acceleration processes in solar flares. The closer proximity of Mercury to the Sun would allow use of a much smaller gamma ray spectrometer system than required at 1 A.U. and would also provide the first opportunity for direct detection of solar neutrons at energies of 1-10 MeV. The Mercury orbiter would also be capable of monitoring 1-500 MeV solar protons to search for decay protons from solar neutron flares and to provide automatic early warning of large proton flares which would be a hazard to manned space operations near Earth and beyond.

1. Introduction. The planet Mercury has remained unexplored since the three Mariner-10 flybys in 1974-1975. The European Space Agency (ESA) has received, but not yet approved, a recent proposal /1/ for a Mercury polar orbiter mission in the 1990's. Although no such mission has yet been considered in the U.S., it could be undertaken in the late 1990's or the post-2000 era by using a modified version of the Mars Observer spacecraft, now planned for launch in 1990-92.

High resolution gamma ray spectrometry /2/ would be an integral part of a planetary observer mission at Mercury, since the absence of an atmosphere would allow geochemical mapping of the surface with a surface resolution approaching 100 kilometers for an orbit of that altitude. An inventory of elemental abundances near the surface, perhaps characteristic of the planetary crust, would significantly advance our limited knowledge of the planet's formation and evolution /3/. The density of Mercury is significantly higher than expected for a lunar-sized planetary body and suggests that an iron core may comprise a large fraction of the planetary mass. Abundance measurements of radionuclides (K, U, and Th) would be especially relevant to determination of the planet's thermal history, including the heating of the core region, and the origin of Mercury's magnetic field, possibly arising from a dynamic molten core. Cooling of this core may have been responsible for Mariner-10 observations of compressive (thrust) faults on the surface due to shrinking of the planetary crust. Although no direct evidence was found for recent tectonic or volcanic activity, indicating relative quiescence in comparison to Earth, the large, smooth plains of Mercury have been attributed to episodes of volcanic activity in Mercury's early history and may be associated with measurable regional differences in surface composition.

The scientific return from a Mercury observer mission could be significantly enhanced by augmenting instrumentation to undertake solar observations during an extended mission phase, particularly since a launch in the late 1990's would allow observations from 0.4 A.U. by the onset of maximum flare activity near the year 2002. Availability of an earth-based orbital platform (i.e., the Solar Maximum Mission satellite) for solar observations, with sensitivity at 1 A.U. at least comparable to that for instruments on the Mercury orbiter at 0.4 A.U., would allow stereoscopic measurements of neutral solar flare radiation. The stereoscopic observations could allow fundamental advances in the understanding of solar flare energy release and particle acceleration processes.

Measured from at least two different heliocentric angles, the directivity of solar gamma rays could be determined for individual flares. Although hard x-ray emission near 100 keV is already known to be isotropic on the basis of previous stereoscopic observations /4/, the heliolongitude distributions of gamma ray flares observed only from earth orbit are not consistent with isotropic photon emission at energies above 300 keV /5/. At high energies above 10 MeV a strong limb-brightening effect is found, consistent with the predicted /6,7,8,9/ bremsstrahlung emission from downward-directed beams of flare-acclerated electrons in the solar chromosphere. Beaming effects for flare-accelerated ions might also be studied with high resolution spectroscopy of gamma ray lines. The coherent doppler effect /10/ produces a dip in the doppler-broadened line profile for the 4.4-MeV line from C^{12} excitation, if the carbon ions have anisotropic distributions. Resolution of individual helium lines at 0.4-0.5 MeV would be indicative of anisotropy for flare-accelerated helium nuclei /11/. Differential line attentuation as a function of flare observation angle could be used to estimate altitudes of flare emission sources in the solar atmosphere as has previously been attempted for 100-keV x-rays /12/.

2. Mercury/Solar Observer Mission Although long thought impossible with available launch technology, the dynamical problem of achieving orbital capture at Mercury after launch from Earth has been solved with ballistic trajectories /13/ which employ multiple flybys of Mercury and Venus. For example, a launch from Earth in 1996 would insure arrival in Mercury orbit with an orbital payload of about 1200 kg in 5.3 years after two flybys of Venus and three of Mercury. A lesser payload of 600 kg, requiring only one Mercury flyby and two Venus flybys, would reduce the time to 2.9 years. Nonballistic trajectories have also been considered which utilize ion propulsion driven by solar electric power /1/ or solar sails /14/.

The mission of a single planetary observer spacecraft to Mercury could be divided into four principal phases: (1) interplanetary cruise with multiple Mercury/Venus flybys and long-term monitoring of solar flare radiation and solar energetic particles in interplanetary space, (2) *in-situ* measurements of magnetospheric fields, plasma, and trapped radiation (if any) after initial injection into a highly eccentric elliptical orbit around Mercury which also allows exploration of the magnetospheric bow shock and magnetotail regions and their interactions with the solar wind, (3) low altitude polar orbit for geochemical mapping, mapping of dayside surface topography, and magnetometer measurements of high-order components in the planetary magnetic field, and (4) long-term solar monitoring and continued planetary observations at least through the years 2002-2006. For this final phase the plane of the spacecraft orbit should be shifted to coincide with the dawn-dusk meridinal plane, which would allow continuous monitoring of transient solar flare events and maximize the probability of stereoscopic observations from Mercury and Earth. This orbit also provides a fixed direction for pointing instruments towards the Sun and removes the need to expend spacecraft power resources on solar tracking.

The difficulties in maintaining a spacecraft in the harsh solar radiation environment at the orbit of Mercury (0.4 ± 0.1 A.U.) would be severe but are not insuperable with present technology. The Helios 2 spacecraft operated in the inner solar system with the same perihelion as Mercury and an aphelion at 1 A.U. for nine years (1976-1984), before succumbing to power losses from radiation darkening of solar panels /15/. Temperatures on Helios near perihleion ranged from -20° (C) in internal components to about 200° (C) on exterior surfaces. Addition of thermal shielding to an observer-type spacecraft, including sun shades for instruments such as the gamma ray system (GRS), would probably not significantly increase the spacecraft payload mass. Improvements in thermal shielding and solar cell technology would allow a mission extending from 1996 through 2006 and possibly beyond.

3. Solar Flare Observations. As a baseline we assume that flare activity during the years 2002-2006 will be simlar that observed in 1980-1984 during the operation of the gamma ray experiment (GRS) on the Solar Maximum Mission (SMM) spacecraft in low-altitude earth orbit. The SMM GRS consisted of seven standard-sized (7.6-cm diam. x 7.6-cm) NaI detectors with active shielding, including a CsI backplate for coincidence analysis of high energy gamma rays and neutrons /16/. With a typical flux sensitivity of $10^{-3}-10^{-2}$ γ/cm^2–sec the SMM GRS detected 150 flares with gamma ray emission at energies above 300 keV, about thirty of which also had detectable emission in individual gamma ray lines /17/. Time durations for measurements of prompt gamma ray emission from these flares were 1-20 minutes, the maximum time being constrained by SMM's dayside orbit. The maximum observed intensity was about 10 γ/cm^2–sec for ten-second bursts from the large flare on June 3, 1980. Fourteen flares produced detectable high energy gamma ray emission in the range 10-140 MeV. The delayed arrival of 50-500 MeV flare neutrons was detected from two of the largest flares.

The gamma ray system on Mars Observer will consist of a single 140-cc detector (HPGe) with a borated plastic scintillator shield and a passive radiator system to keep the detector cooled near 100° (K) and maintain the nominal line energy resolution of a few keV at MeV line energies. If used for a Mercury orbiter mission, this GRS would require several additional kilograms of thermal shielding for the passive radiator system to achieve the same level of cooling. Although even the Mars Observer GRS at 1.524 A.U. will probably detect the most intense solar flares during the 1991-1995 flare activity period, the factor of 9-26 increase in solar radiation intensity from Mars to Mercury (0.3-0.5 A.U.) would make the Mercury orbiter preferable for solar flare observations which could be correlated to those made from earth orbit.

Metzger et al /2/ have calculated the sensitivity of an 80-cc HPGe detector for planetary gamma ray lines observed above local spacecraft background. The three-sigma lower limit is $1.2x10^{-2}$ γ/cm^2–sec for measurements of the 2.6-MeV thorium line over time intervals of one hour. Since the minimum flux sensitivity scales with time t as $t^{-1/2}$, the sensitivity to solar flare gamma rays (i.e., 2.2-MeV line) for time intervals of 10 sec, 60 sec, and 20 min would correspond to minimum fluxes of 0.3, 0.1, and 0.02 γ/cm^2–sec, respectively. At 4-8 MeV the lower photopeak efficiency and energy resolution may be offset by reduced background levels. The minimum detectable fluxes for the 140-cc detector on Mars Observer will be about a factor of two lower.

Observations of continuum gamma ray emission at 0.3-10 MeV and above may require augmentation of the Mars Observer GRS for solar flare work. Two standard-size NaI detectors at 0.4 A.U., adding a total payload mass of 6-8 kg to the Mercury orbiter, would roughly match the flare-size sensitivity of the SMM gamma ray experiment at 1.0 A.U. Measurements of the continuum emission would be enhanced by subtraction of gamma line fluxes measured with the HPGe detector. Two-detector coincidence analysis would also allow separation of gamma ray fluxes above 10 MeV from the fluxes for solar neutrons above 20 MeV, since neutrons would usually trigger only one of the two detectors /18/. Alignment of the NaI detectors coaxially within thirty degrees of the Sun would allow measurements of high energy gamma rays above 10 MeV by analysis of concident events in both detectors, but this alignment would not be possible without continuous mechanical tracking of the Sun in an orbit like that of Mars Observer, for which the orbital plane will at an angle of about 30° to the noon-midnight meridian of Mars. Continuous alignment within a few degrees of the sunward direction could be maintained without aetive solar tracking by using the dawn-dusk polar orbit.

The first direct measurements of 1-10 MeV neutrons from solar flares at 0.4-A.U. flux levels of ~ 1 n/cm^2–sec /19/ could be made by a Mercury orbiter mission, since the probability of solar neutron decay is $10^1 - 10^3$ times higher in that energy range at 1 A.U. than at 0.4 A.U. At 1-6 MeV these neutrons could be detected with the borated plastic scintillator shield /20/ of the GRS, for which the low efficiency of MeV neutron scattering would be compensated by the large shield area. The HPGe detector itself would be sensitive to 1-16 MeV neutrons with an efficiency $\lesssim 0.1/\mathrm{cm}^2$, since the Ge^{72} (n,nγ) reaction produces a broad gamma ray line at 693 keV /21/.

Observations of delayed flare emission and nonrelativistic neutrons would benefit from a Mercury orbit with continuous solar visibility. The lower limit of 50 MeV for SMM GRS detection of solar flare neutrons was largely due to limited observation time on the earth's dayside. Solar neutrons at energies near one MeV would require about one hour to reach 0.4 A.U. after arrival of the initial gamma ray emission from a flare. Long-term flare visibility would also benefit observations of solar gamma rays produced in delayed particle acceleration phases or by secondary interaction products with long time constants for gamma emission.

Solar flare neutrons at energies of 1-500 MeV can also be measured indirectly with charged particle detectors as decay protons in interplanetary space /22/. The Störmer cutoffs associated with the magnetic field of Mercury are low enough to allow access of MeV protons even to low altitudes near the magnetic dipole equator. Correlation of decay proton measurements from Mercury with those made near Earth would provide new data on diffusion rates in the interplanetary magnetic field for solar protons from a common flare source. Long-term monitoring of the 1-500 MeV solar flare proton intensities at the orbit of Mercury would also provide an invaluable early warning capability to protect manned space operations at 1 A.U. and beyond from flares with large intensities of high energy protons and ions.

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